Large Aperture “Photon Bucket” Optical Receiver Performance in High Background Environments

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Polished Panel System Concept

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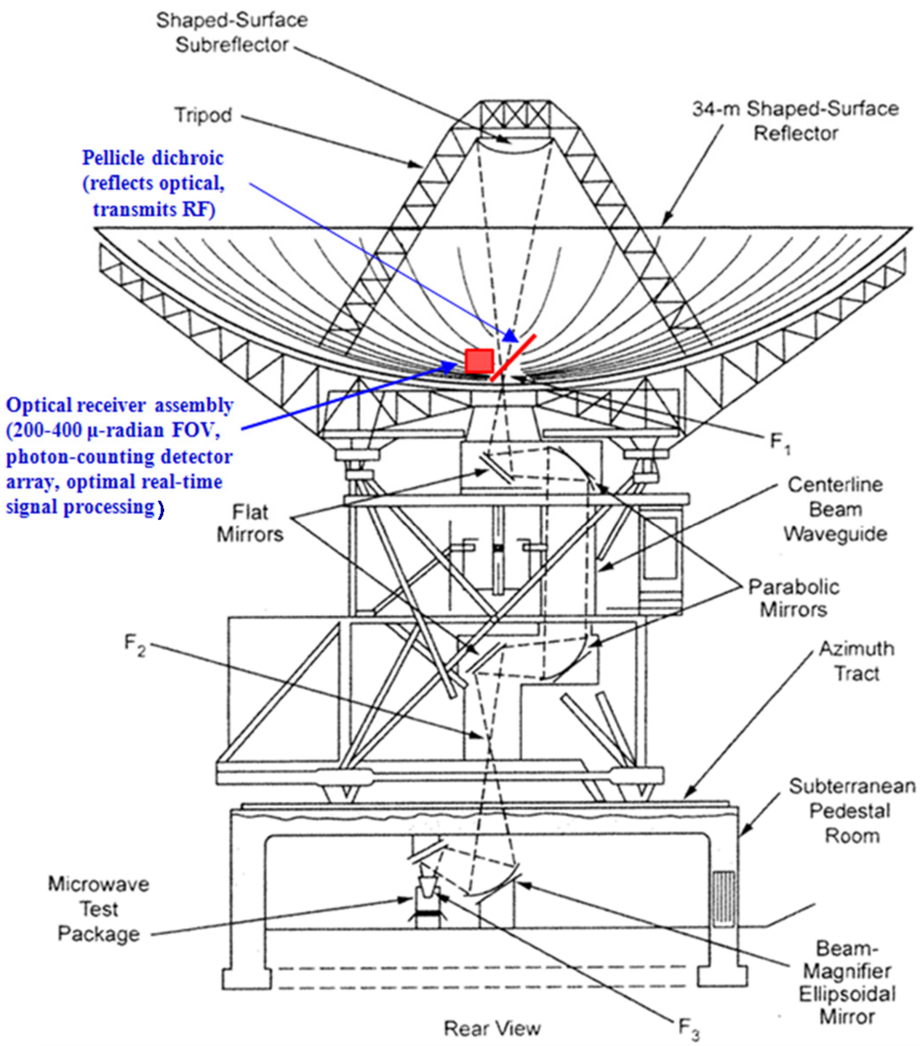
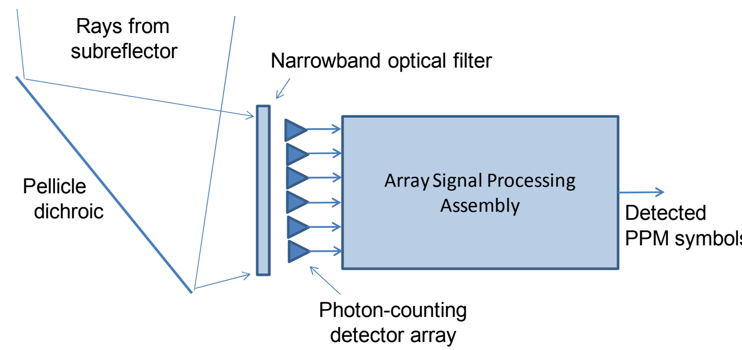
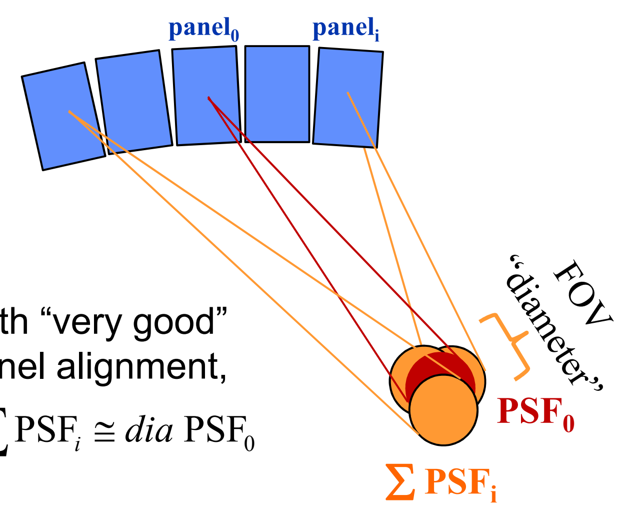


Optical communications receiver assembly placed at F1: RF/Optical dichroic, optical filter, detector array, high-speed signal-processing equipment.



Functional block diagram of Optical Receiver Assembly, placed on the main reflector at F1, near the entrance to the RF beam waveguide in a DSN 34-meter antenna.

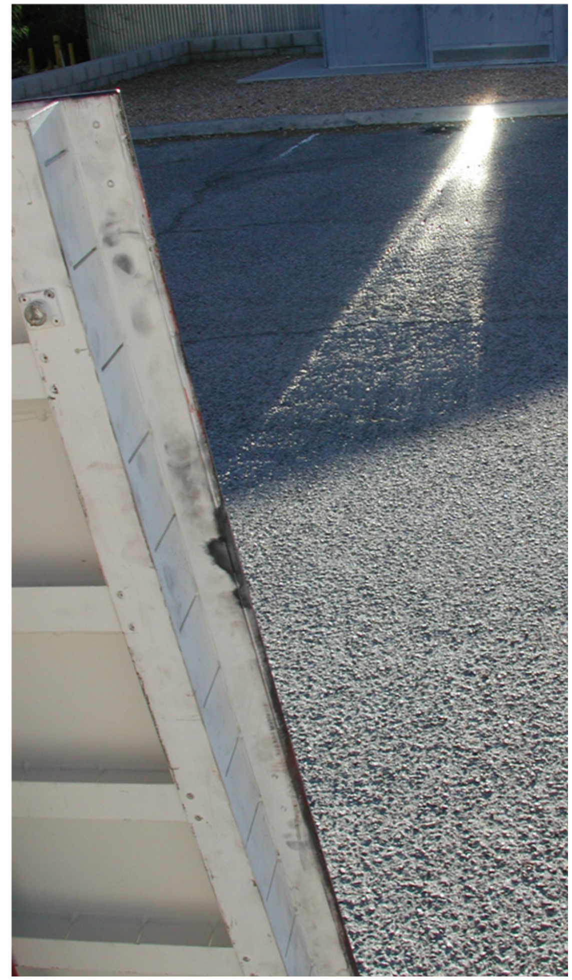


With "very good" panel alignment,

$$dia \sum \text{PSF}_i \cong dia\ \text{PSF}_0$$

DSN polished panel, initial daytime visual tests

DSN polished panel reflectivity, surface accuracy test



DSN polished panel ray concentration

Background Radiation and Polished Panel PSF

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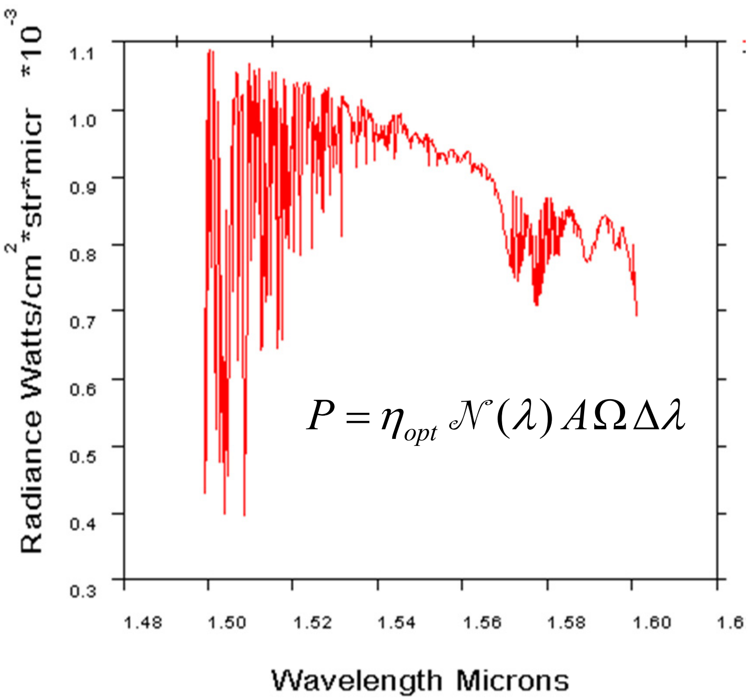


Example of sky radiance for a desert model, at "sun-earth-probe" (SEP) angle of 10 degrees.

$$\Omega = \pi R^2 / f_{eff}^2$$

$$n_b = \eta_{opt} \eta_d \, \pi R^2 \mathcal{N}(\lambda) A \Delta\lambda / h\nu \, f_{eff}^2$$

$$K_b = \eta_{opt} \eta_d \, \mathcal{N}(\lambda) A \Omega \Delta\lambda \, \tau / h\nu \equiv I_b \, A$$

Average background count K_b depends on background intensity in photo-counts/meter^2, and collecting area A in meter^2

$\mathcal{N}(\lambda)$ - Spectral radiance function

A - Receiver collecting area

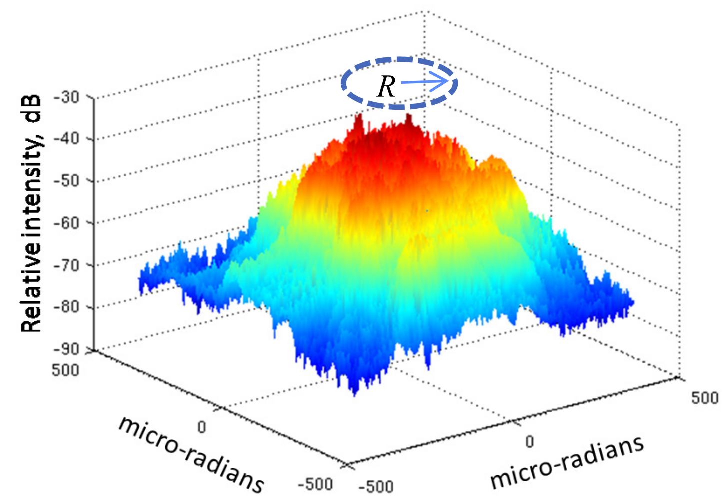
Ω - Receiver FOV, steradians

λ - Optical signal wavelength

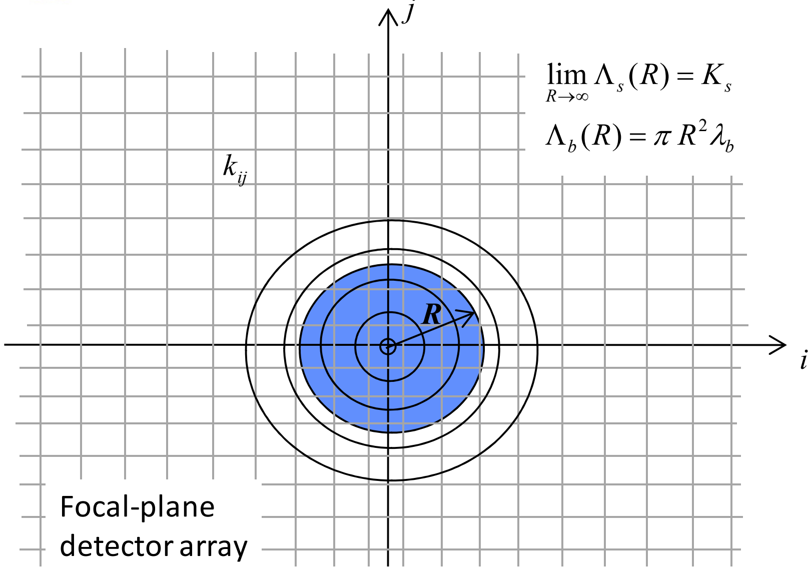
$\Delta\lambda$ - Narrowband filter bandwidth

η_{opt} - Optical system throughput

η_d - Detection efficiency



Example of PSF generated by a realistically modeled panel surface error distribution, showing high concentration of signal energy in the inner +/- 125 micro-radians from center. Horizontal axes in μrads, vertical axis in dB (intensity, arbitrary units)



Detector-plane model of photon-counting Array and PSF with small pointing offsets.

Poisson calculation:

$$P_M^l(C) \geq \sum_{k=1}^{\infty} \frac{(\Lambda_s(R)+\Lambda_b(R))^k}{k!} \exp[-(\Lambda_s(R)+\Lambda_b(R))] \times \left\{ \sum_{j=0}^{k-1} \frac{(\Lambda_b(R))^j}{k!} \exp[-(\Lambda_b(R))] \right\}^{M-1}$$

$$\boxed{P_M^u(E) \equiv 1 - P_M^l(C) \geq P_M(E) \cong P_M(E)}$$

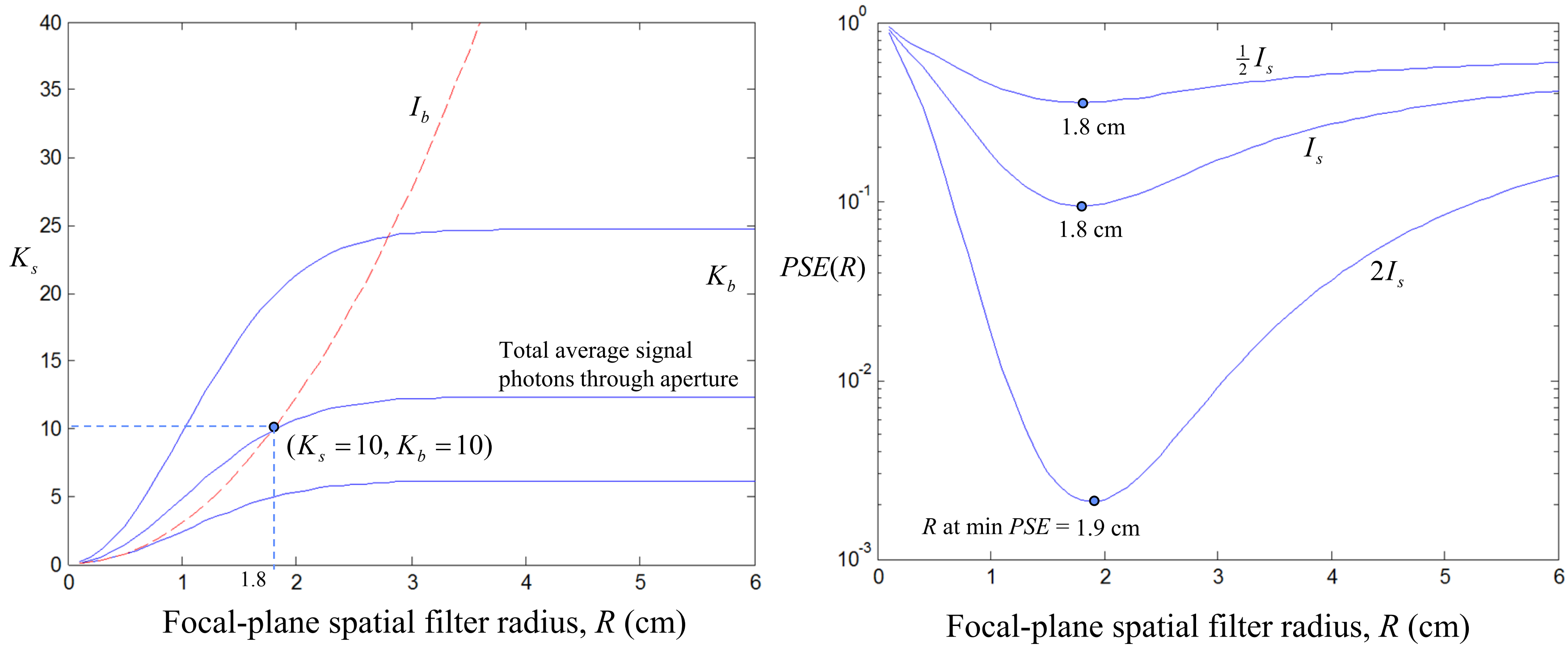
Gaussian approximation: $P_M(C) \cong \int_{-\infty}^{\infty} dy\, Gsn[\Lambda_s(R) + \Lambda_b(R), y] \left[\int_{-\infty}^{y} dx\, Gsn[\Lambda_b(R), x] \right]^{M-1}$

- Laser transmitter appears as a point source, therefore …
- Average signal count can be expressed as: $K_s = I_s A$
- With fixed field-of-view Ω , the average background count can be expressed as: $K_b = I_b A$

$$\Delta K_s = I_s \, \Delta A$$

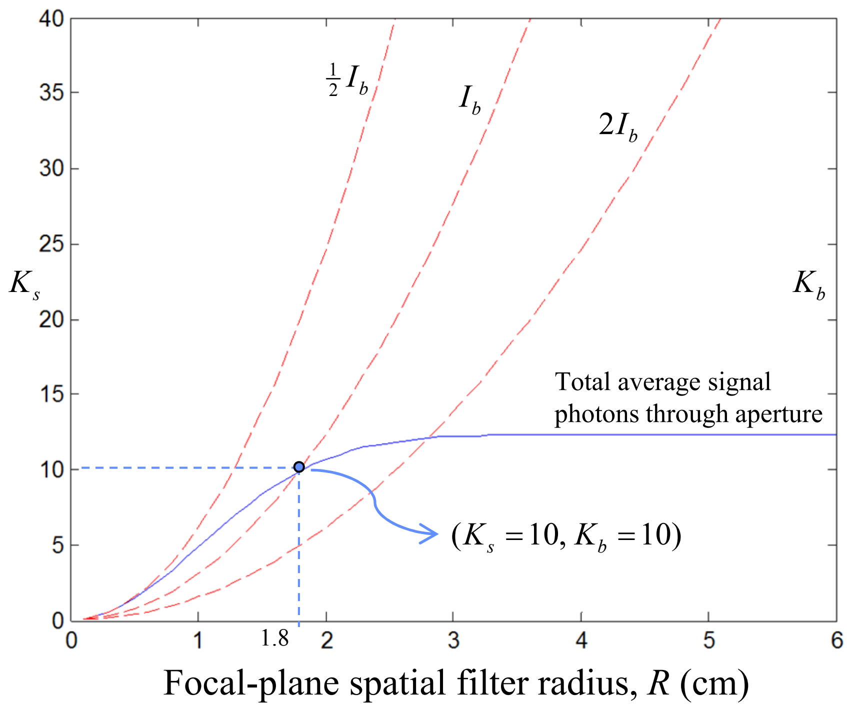
$$\Delta K_b = I_b \, \Delta A = (I_b / I_s) \Delta K_s$$

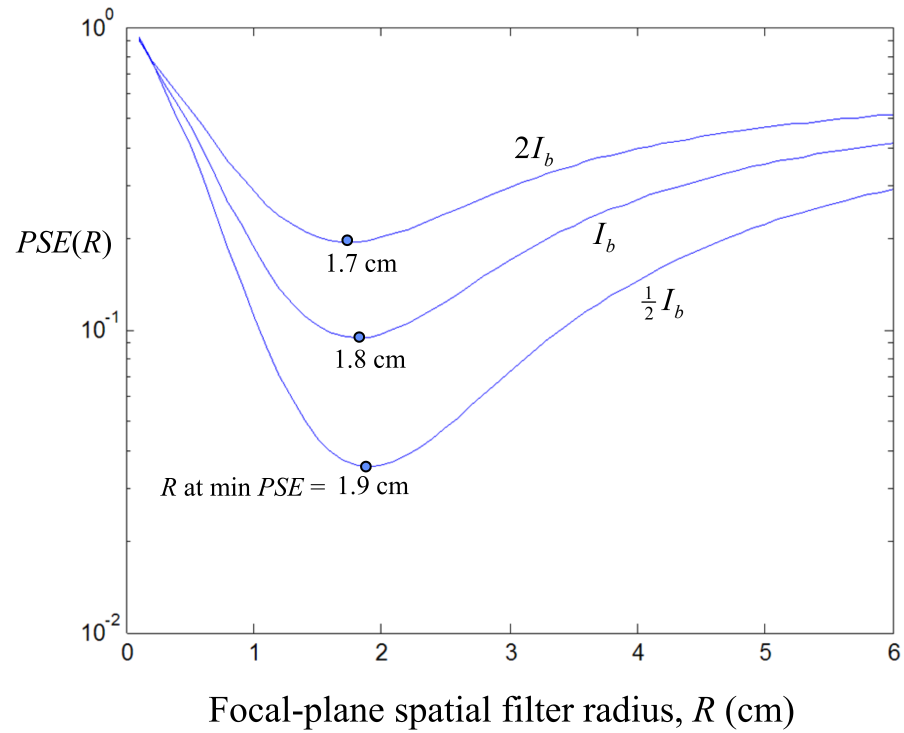
Focal-plane optimization with constant background intensity



2D Gaussian PSF model, standard deviation $\sigma_{PSF} = 1\,\text{cm}$

Focal-plane optimization with constant signal intensity





2D Gaussian PSF model, standard deviation $\sigma_{PSF} = 1\,\text{cm}$

Computation of Constant PSE Contours

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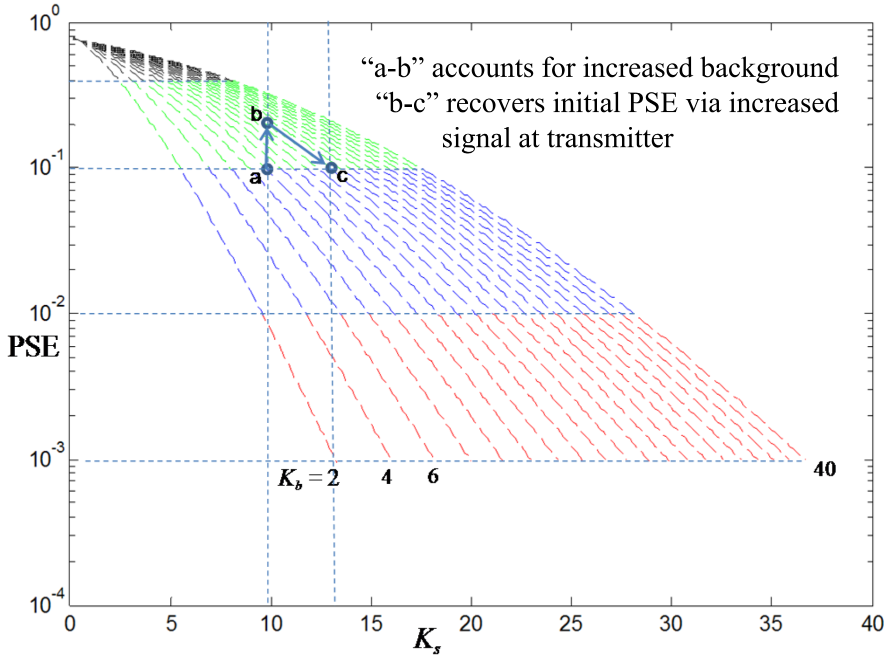
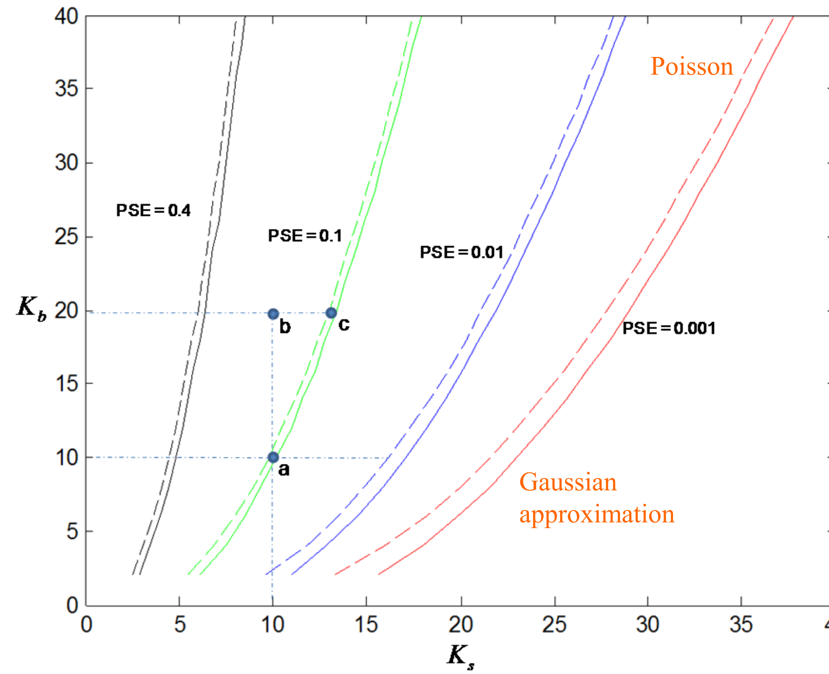
Poisson computation of PSE vs K_s



Probability of symbol error, PSE, for M = 4 PPM signaling as a function of K_s, for a range of background energies, K_b.

Constant PSE contours, (K_s, K_b) plane



Contours of constant symbol-error probability, PSE, over the (K_s, K_b) plane. Dashed curves were computed using Poisson probabilities, solid curves computed via the faster Gaussian approximation.

Tangent-Line Approximation and Exact Solution

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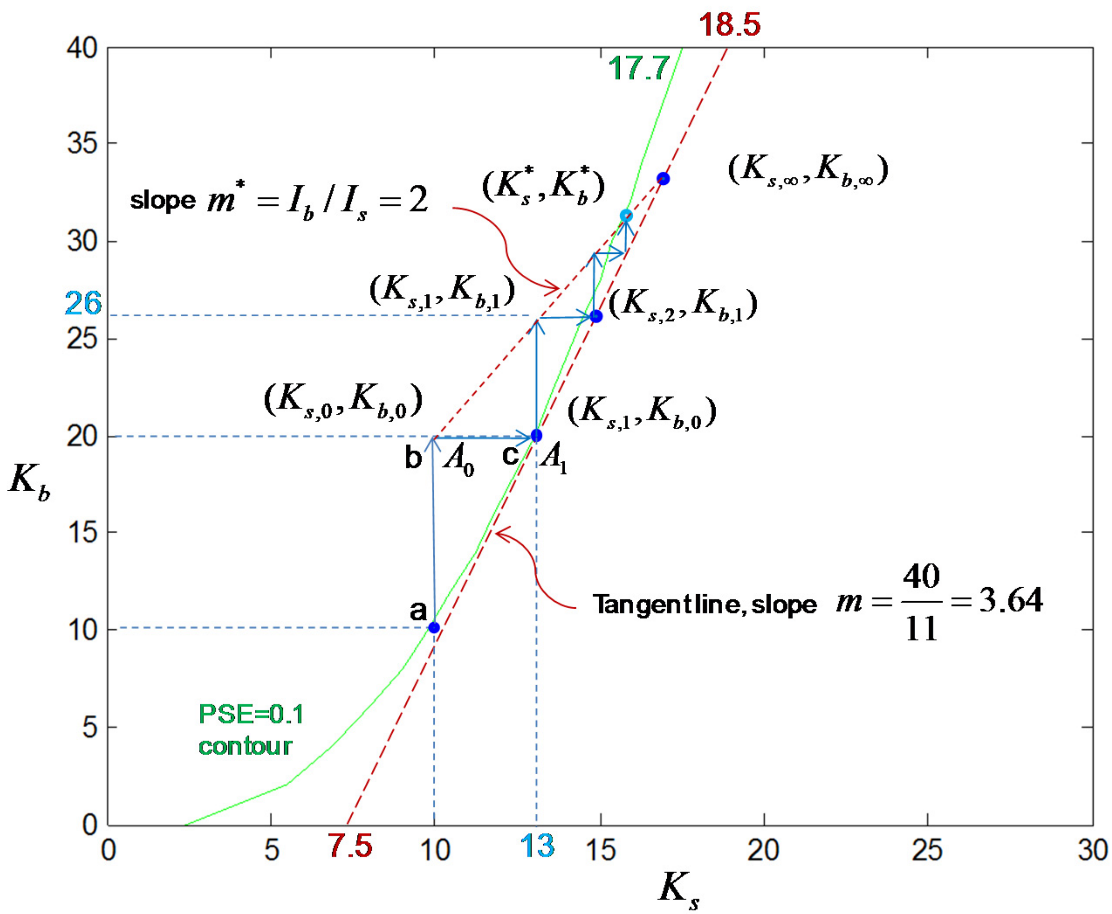


Compensation for excess background energy by increasing signal energy via aperture expansion, with the goal of maintaining constant symbol-error probability of PSE = 0.1.

$$K_{s,1} = K_{s,0} + \Delta K_{s,1} = I_s(A + \Delta A_1)$$

$$K_{b,1} = K_{b,0} + \Delta K_{b,1} = I_b(A + \Delta A_1)$$

$$= \frac{I_b}{I_s}(K_{s,0} + \Delta K_{s,1})$$

$$K_{s,2} = K_{s,0} + \Delta K_{s,1} + \frac{I_b}{I_s m}\Delta K_{s,1}$$

$$K_{s,3} = K_{s,0} + \Delta K_{s,1} + \frac{I_b}{I_s m}\Delta K_{s,1} + \left(\frac{I_b}{I_s m}\right)^2 \Delta K_{s,1}$$

$$K_{s,\infty} = K_{s,0} + \Delta K_{s,1}\sum_{k=0}^{\infty}(I_b / I_s m)^k$$

$$= K_{s,0} + \Delta K_{s,1}\left(1 - \tfrac{I_b}{I_s m}\right)^{-1}$$

$$= K_{s,0} + \Delta K_{s,1}\,\alpha/(\alpha - 1); \quad \alpha = I_s m / I_b$$

Similarly for K_b: $\quad K_{b,\infty} = (I_b / I_s) K_{s,\infty}$

for $\alpha > 1$ since $\lim_{\alpha \to 1} \alpha/(\alpha - 1) = \infty$

Example: $K_{b,0} = 20, \quad K_{s,0} = 10, \quad \Delta K_{s,1} \cong 3, \quad \Delta K_{b,1} \cong 6,$

$$m = 40/11 = 3.64 \qquad \alpha/(\alpha - 1) = 2.22$$

$$K_{s,\infty} = 10 + 6.67 = 16.67 \qquad K_{b,\infty} = 2K_{s,\infty} = 33.3$$

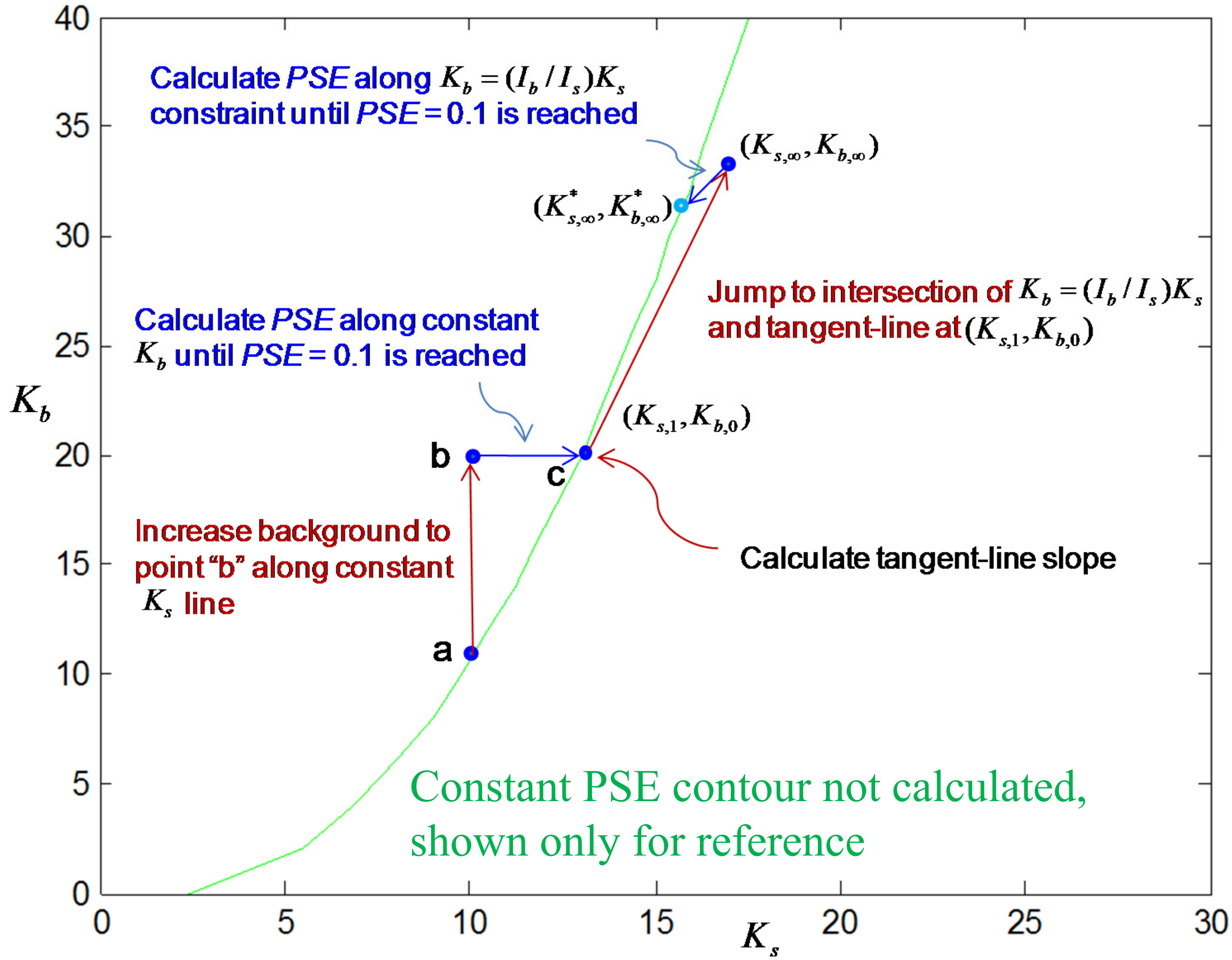
$$(K_{s,i}, K_{b,i}), \quad i = 0, 1, 2, \dots \qquad m^* = I_b / I_s$$

$$(K_s^* = 15.5, K_b^* = 31.5)$$

$$\boxed{\Delta A \cong 55\% \quad \Delta D \cong 24\%}$$

Therefore, only 55% increase in receiver collecting area (or 24% increase in receiver diameter) is required to compensate for 100% increase in background energy.

Proposed "simpler" algorithm for calculating final (K_s, K_b) values



Other potential "simpler" algorithms

1. Gaussian approximation:

- Compute *PSE* contour using the Gaussian approximation
- Determine intersection of $K_b = (I_b / I_s)K_s$ line with Gaussian contour
- Calculate *PSE* along $K_b = (I_b / I_s)K_s$ constraint

2. Constrained trajectory solution:

- Starting at (0,0) calculate *PSE* along the $K_b = (I_b / I_s)K_s$ trajectory using Poisson model until desired *PSE* is reached

Evaluation and Comparison of Reduced Complexity Algorithms remains the subject of future work